First measurement of the Gerasimov-Drell-Hearn integral for ^{1}H from 200 to 800 MeV

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A direct measurement of the helicity dependence of the total photoabsorption cross section on the proton was carried out at MAMI (Mainz) in the energy range $200 < E_\gamma < 800$ MeV. The experiment used a 4π detection system, a circularly polarized tagged photon beam and a frozen spin target. The contributions to the Gerasimov-Drell-Hearn sum rule and to the forward spin polarizability γ_0 determined from the data are $226\pm5(stat) \pm 12(sys)$ μb and $-187\pm8(stat) \pm 10(sys)$ 10^{-6}fm^4, respectively, for $200 < E_\gamma < 800$ MeV.

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I. INTRODUCTION

In a recent paper [1] we have published the first data on the helicity dependence of the $\gamma p \to N\pi$ reactions in the energy range from 200 to 450 MeV. In the present paper we present the helicity dependence of the total photoabsorption cross section on the proton in the photon energy range from 200 to 800 MeV. These data give, in particular, important experimental information about the Gerasimov-Drell-Hearn (GDH) sum rule and the forward spin polarizability γ_0.

The GDH sum rule relates the total absorption cross section of circularly polarized photons on longitudinally polarized nucleons to the static properties of the nucleon [2]. The two relative spin configurations, parallel or antiparallel, determine the two absorption cross sections $\sigma_{3/2}$ and $\sigma_{1/2}$. The integral over the photon energy ν of the difference of

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these two cross sections, weighted by the inverse of ν, is related to the mass, M, and anomalous magnetic moment, κ, of the nucleon as follows:

$$\int_{\nu_0}^{\infty} (\sigma_{3/2} - \sigma_{1/2})\, \frac{\mathrm{d}\nu}{\nu} = \frac{2\pi^2\alpha}{M^2}\kappa^2 \tag{1}$$

where ν_0 is the pion photoproduction threshold and α the fine-structure constant. In a similar way, the forward spin polarizability γ_0 can be expressed as:

$$\gamma_0 = -\frac{1}{4\pi^2} \int_{\nu_0}^{\infty} (\sigma_{3/2} - \sigma_{1/2})\, \frac{\mathrm{d}\nu}{\nu^3} \ . \tag{2}$$

The GDH sum rule, formulated in the 1960's, rests upon basic physics principles (Lorentz-invariance, gauge invariance, unitarity) and an unsubtracted dispersion relation applied to the forward Compton amplitude. Due to its fundamental character this prediction requires an experimental verification which has been awaiting technical developments that have only recently been achieved.

In the absence of any direct experimental result some theoretical predictions of the GDH integral have been made in the past years. They are compared to the GDH sum rule in Table I. All predictions were based on multipole analyses of the existing single pion photoproduction data (mainly unpolarized differential and total cross sections and some single polarization observables) and included an evaluation of the contribution of double pion photoproduction processes. With the exception of Ref. [5], this contribution has been taken from Ref. [3]. In Ref. [8], an additional contribution due to multi-hadron production processes was phenomenologically evaluated using a Regge type approach.

Apart from Ref. [8], all of the theoretical predictions consistently exceed the sum rule value for the proton while for the neutron they come out much smaller than the sum rule. However, the GDH integrand is an oscillating function of photon energy, due to multipole contributions of alternating sign. Therefore, as pointed out in Ref. [7], a reliable prediction requires a very high accuracy that has probably not been reached by any of the existing models, in particular for the neutron. Precise experimental data are required to pin down the detailed behaviour of the GDH integrand.

II. EXPERIMENTAL SETUP

The experimental setup has been described previously in detail [1,9] and only the main characteristics are given here. The experiment was carried out at the tagged photon facility [10] of the MAMI accelerator in Mainz. Circularly polarized photons were produced by bremsstrahlung of longitudinally polarized electrons [11]. The electron polarization (routinely about 75%) was monitored during the data taking by means of a Møller polarimeter with a precision of 3%.

The photon energy was determined by the Glasgow-Mainz tagging spectrometer having an energy resolution of about 2 MeV [10]. The tagging efficiency was monitored with an accuracy of 2% by an e^+e^- detector placed downstream of the main hadron detector [9].

Longitudinally polarized protons were provided by a frozen-spin butanol (C_4H_9OH) target [12]. The proton polarization was measured using NMR techniques with a precision of 1.6%, the target density was known with a precision of 1%. Maximum polarization values close to 90% were obtained with a typical relaxation time of $\simeq 200$ hours.

Photoemitted hadrons were registered by a $\approx 4\pi$ sr system based on the large acceptance detector DAPHNE [13] complemented by detectors [14,15] to extend the forward polar angle acceptance.

DAPHNE is essentially a charged particle tracking detector with cylindrical symmetry. An outer double scintillator-absorber sandwich also allows the detection of neutral pions with a moderate $(15-20\%)$ efficiency. It covers polar angles from $\vartheta_{lab} = 21°$ to $\vartheta_{lab} = 159°$.

III. DATA ANALYSIS

In this paper, data recorded by the DAPHNE detector only are presented. An inclusive method of data analysis has been developed to determine the total absorption cross section. It has already been applied to an unpolarized measurement. Since its features are described in [9,16], only the general characteristics will be recalled here.

A large fraction of the total photoabsorption cross section (σ_{tot}) can be directly accessed by measuring the number of events with charged hadrons in the final state (N_{ch}) detected inside the DAPHNE acceptance. Most of the remaining part is deduced from the measured number of π^0 events, with no accompanying charged particle observed (N_{π^0}), by

using the π^0 detection efficiency ($\overline{\epsilon}_{\pi^0}$) evaluated by a simulation. Since $\overline{\epsilon}_{\pi^0}$ is finite for all π^0 energies and angles, no extrapolation is needed for the partial channels having at least one neutral pion in the final state. A small correction ($\Delta N_{\pi^0\pi^0,\eta}$) has to be made since processes involving more than one π^0 in the final state are not included in the evaluation of $\overline{\epsilon}_{\pi^0}$. An additional correction ($\Delta N_{\pi^\pm}$) is needed to take into account the fraction of the events from the charged pion channels ($n\pi^+$, $p\pi^+\pi^-$) emitted into the angular and momentum regions outside of the detector acceptance. For $E_\gamma > 200$ MeV, the region for which the data are presented, the lower momentum limit for the photoemitted π^+ from the $n\pi^+$ reaction is above the detection threshold. Therefore, no correction for the losses due to the detector momentum acceptance is necessary for this channel.

Using the notation above, σ_{tot} can be written as:

$$\sigma_{tot} \propto N_{ch} + N_{\pi^0} \cdot (\overline{\epsilon}_{\pi^0})^{-1} + \Delta N_{\pi^0\pi^0,\eta} + \Delta N_{\pi^\pm}.$$

In Fig. 1, the values of σ_{tot} obtained with an unpolarized liquid hydrogen target during a test run, carried out prior to the main experiment, are shown. In this case, $\Delta N_{\pi^\pm}$ (about 5% of σ_{tot}) was evaluated starting from the experimental single charged pion spectra. The total systematic error on the data is $\simeq \pm 4\%$ of σ_{tot}.

In the same figure, our data are compared to previous results [9,17] and to the HDT prediction from Hanstein et al. [18] (up to $E_\gamma = 450$ MeV), the SAID [19] multipole analysis and the Unitary Isobar model (UIM) [20]. The UIM model takes into account double pion and η photoproduction in addition to single pion production. The good agreement found with the old data and with the different models, demonstrates that the detector response is well understood.

In the analysis of the data from the polarized butanol target, the background contribution from the reactions produced on the unpolarized C and O nuclei of the target could not be fully separated from the polarized H contribution [1]. The inclusive method was then used to evaluate the difference $\Delta\sigma = (\sigma_{3/2} - \sigma_{1/2})$ of the two helicity dependent total cross sections $\sigma_{3/2}$ and $\sigma_{1/2}$. However, the extrapolation of the charged pion photoproduction channels could not be done as in the unpolarized case. In the following, we briefly describe the procedures that were used.

The angular extrapolation needed for the ($n\pi^+$) channel was evaluated using the SAID [19] multipole analysis, which reproduced well our previous experimental results of the helicity dependence of this reaction channel in the $\Delta(1232)$ resonance region [1]. As a systematic error, $\pm 5\%$ of the evaluated correction is taken for $E_\gamma < 500$ MeV, while at higher energies, $\pm 20\%$ of the evaluated correction is assumed.

The correction for the unmeasured part of the $p\pi^+\pi^-$ channel was evaluated under the assumption that the helicity asymmetry $(\sigma_{3/2} - \sigma_{1/2})/(\sigma_{3/2} + \sigma_{1/2})$ in the unmeasured part is the same as the one measured inside the DAPHNE acceptance [21]. The correction for the $p\pi^0\pi^0$ channel was evaluated similarly [22]. For the $p\eta$ channel, which couples to the S_{11} resonance and therefore has a dominant $\sigma_{1/2}$ contribution, an helicity asymmetry of -0.97 was assumed, following the calculation of Ref. [23]. For the last three contributions, a systematic error equal to $\pm 50\%$ of the evaluated correction is assumed.

The remaining sources of systematic errors are due to uncertainties in wire chamber efficiency (1% of N_{ch}) and π^0 detection efficiency (4% of $N_{\pi^0} \cdot (\overline{\epsilon}_{\pi^0})^{-1}$). The dominant contribution to the systematic error stems from uncertainties in photon flux, target density and beam and target polarizations; their sum in quadrature is about 4% of $\Delta\sigma$. Tab. II summarizes for two energies the different contributions to $\Delta\sigma$ together with their systematic errors and gives the total systematic error obtained by summing in quadrature all contributions.

IV. RESULTS

The analysis procedure as described above results in the total cross section difference $(\sigma_{3/2} - \sigma_{1/2})$ depicted in Fig. 2 [16]. It is compared with the sum of our previously published helicity differences for the $n\pi^+$ and $p\pi^0$ channels in the Δ region [1]. The good agreement found between the different analyses gives us confidence in their reliabilty. In the same figure, our data are also compared to the HDT [18], SAID [19], and UIM [20] analyses.

In the Δ resonance region, there is a rather good agreement between experiment and theories. In the second resonance region, a significant contribution from double pion photoproduction is clearly visible. This feature is not completely reproduced by the UIM model.

In Fig. 3 the experimental running GDH integral (left-hand side of eq.1) is displayed and compared to the model predictions. The integration starts at $E_\gamma = 200$ MeV and the upper integration limit is taken as the running variable. The measured value of the GDH integral between 200 and 800 MeV amounts to 226 ± 5 $(stat) \pm 12$ (sys) μb.

Due to the ν^{-3} weighting, the γ_0 running integral is almost saturated by $E_\gamma = 800$ MeV. The value of the γ_0 integral between 200 and 800 MeV amounts to $[-187 \pm 8\ (stat) \pm 10\ (sys)] \cdot 10^{-6}$ fm^4.

V. DISCUSSION

Although the measured photon energy interval is too narrow to draw any definitive conclusion, a reasonable estimate of the GDH sum rule value can be deduced if we use the existing models for the evaluation of the missing contributions. The UIM model [20] gives a contribution of -30μb for $E_\gamma < 200$ MeV and $+40\mu$b for $800 < E_\gamma < 1650$ MeV. For $E_\gamma > 1650$ MeV, Ref. [8] gives a contribution of -26 μb. The combination of our experimental result with these predictions yields an estimate (210 μb) which within the experimental errors is consistent with the GDH sum rule value (1). It should be kept in mind that, especially above $E_\gamma = 800$ MeV, none of the models has yet been validated experimentally and only a measurement in this energy region can lead to a definitive conclusion about the high energy contribution to the GDH-integral. Our collaboration is performing such a measurement at ELSA (Bonn) up to $E_\gamma \simeq 3$ GeV, and extensions to higher energies are under way or in preparation at Jefferson Lab [24] and SLAC [25].

In case of the γ_0-integral (2) the contribution from $E_\gamma < 200$ MeV is important, the UIM prediction being $+104 \cdot 10^{-6}$ fm^4. The missing high energy contribution, according to UIM and Ref. [8], is $-3 \cdot 10^{-6}$ fm^4 only. The combination with our experimental result gives an estimate of $-86 \cdot 10^{-6}$ fm^4 for γ_0 .

Several predictions, based on dispersion relations [26,27] and chiral perturbation theory [28–32], have been made for γ_0 in the last few years, see table III. They range from (-380 to $+460$) $\cdot 10^{-6}$ fm^4. Our result is close to the range of γ_0 values predicted by dispersion theory.

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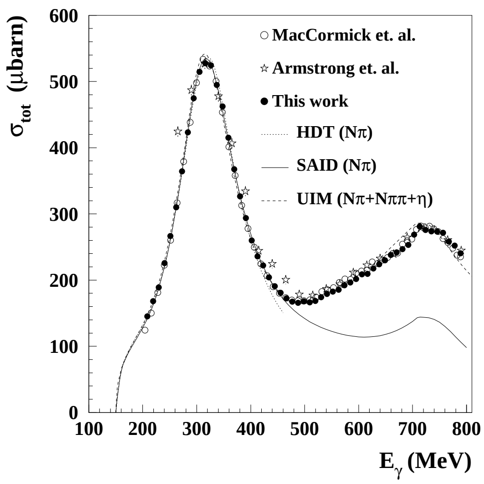

FIG. 1. The unpolarized total photoabsorption cross section on ^{1}H obtained in this work is compared to previous results [9] (open circles), [17] (stars) and to the HDT [18], SAID [19] and UIM [20] analyses. The statistical error bars are smaller than the size of the symbols.

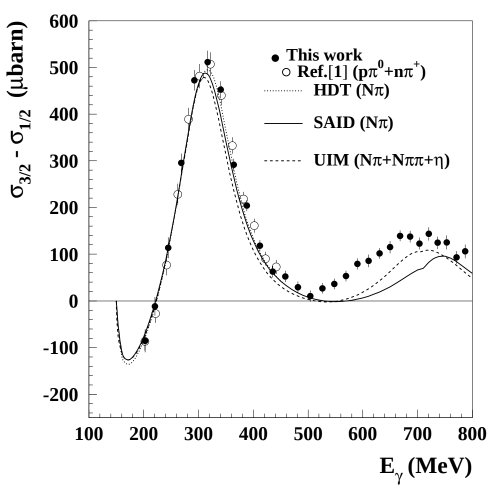

FIG. 2. The total cross section difference ($\sigma_{3/2} - \sigma_{1/2}$) on ^{1}H is compared to previous results [1] (open circles) and to the predictions of the HDT [18], SAID [19] and UIM [20] analyses. Only statistical errors are shown.

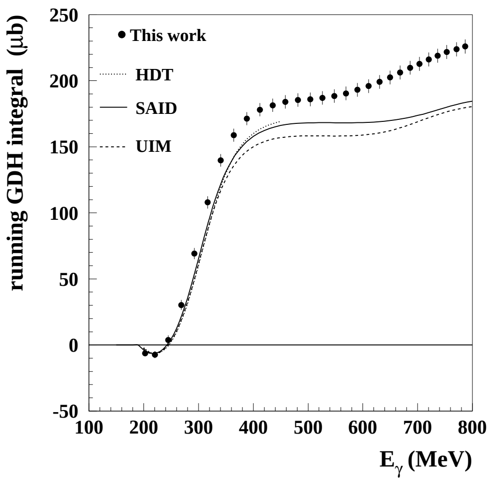

FIG. 3. The running GDH integral obtained in this work starting at 200 MeV is compared to the model predictions. Only statistical errors are shown.

TABLE I. The GDH sum rule (eq. 1) for the proton (I_p^{GDH}) and the neutron (I_n^{GDH}) is compared with some theoretical predictions.

	I_p^{GDH} (μb)	I_n^{GDH} (μb)	$I_{(p-n)}^{GDH}$ (μb)
GDH sum rule	205	233	- 28
Karliner [3]	261	183	78
Workman-Arndt [4]	260	157	68
Burkert-Li [5]	223		
Sandorfi et al. [6]	289	160	129
Drechsel-Krein [7]	261	180	81
Bianchi-Thomas [8]	207± 23	226 ± 22	-19 ±37

TABLE II. The different contributions (in μb) to $\Delta\sigma$ and to the total systematic error are shown at E$_\gamma$=317 MeV and E$_\gamma$=753 MeV. The symbol $\delta(t,\gamma)$ denotes the sum in quadrature of the systematic errors related to photon flux, beam and target polarizations, and target density. See the text for the explanation of the other symbols.

E$_\gamma$ (MeV)	$\Delta\sigma$ $(\mu$b)	N_{ch}	$N_{\pi^0} \cdot (\overline{\epsilon}_{\pi^0})^{-1}$	$\Delta N_{\pi^\pm}$	$\Delta N_{\pi^0\pi^0,\eta}$	$\delta(t,\gamma)$	total sys. err.
317	511	315 ± 3	213 ± 9	-17 ± 1		21	23 μb
753	125	107 ± 1	22 ± 1	-7 ± 4	3 ± 2	5	7 μb

TABLE III. Theoretical predictions of the forward spin polarizability γ_0 of the proton (in units of 10^{-6}fm^4).

Dispersion theory	γ_0	ChPT	γ_0
Babusci et al. [26]	-150	Bernard et al. [28]	+460
Drechsel et al. [27]	-80	Hemmert et al. [29]	+200
		Ji et al. [30]	-380
		Kumar et al. [31]	-380
		Gellas et al. [32]	-100